

COMMERCIAL APPLICATIONS OF NEW PHOTOVOLTAIC TECHNOLOGIES

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ABSTRACT

The National Renewable Energy Laboratory (NREL) has directed and managed photovoltaic (PV) research and development (R&D) activities for the Department of Energy for more than 13 years. The NREL budget for these activities is almost \$33 million for Fiscal Year 1991. With the world's increasing concern for the environment and the United States' renewed apprehension over secure and adequate energy supplies, the use of semiconducting materials for the direct conversion of sunlight to electricity--photovoltaics--is an excellent example of government-supported high technology ready for further development by U.S. companies. This paper will describe some new PV technologies and their research progress, some commercial applications of PV, and NREL's technology transfer activities for helping U.S. industry in its efforts to bring new products or services to the marketplace.

INTRODUCTION

The Solar Energy Research Institute (now the National Renewable Energy Laboratory) was established by Congress in 1974 as the nation's primary center for solar energy R&D. With almost 500 staff members, NREL is involved in scientific and engineering activities ranging from basic materials science, applied research directed towards performance improvements or cost reductions, and systems engineering directed toward project design and evaluation. Approximately 80 NREL staff are directly involved in PV research. Of the \$33 million allocated for NREL's PV research during Fiscal Year 1991, over half was for subcontracted research by universities and private companies. Much of the subcontracted research with industry is cost-shared; that is, a company provides funds of its own to add to NREL subcontract funds. NREL's cost-shared subcontracted research with private companies overcomes many technology transfer barriers because industry researchers are directly supported for further development of PV technology.

NEW PV TECHNOLOGIES

Some of the PV technologies new to the marketplace are not at all new to PV researchers. NREL PV researchers have worked on these technologies since the late 1970s. The crystalline silicon PV technology was discovered in the mid-1950s and is still the most widely sold PV technology, principally because of its high efficiency and long-term stability. The new technologies, however, have the potential of being cheaper than crystalline silicon. Their potential for lower cost arises from significantly lower material requirements, lower energy processing, or higher volume production capabilities. Additional R&D, for example, to improve conversion efficiencies, is required for the new technologies to reach the marketplace. The new PV technologies in NREL's PV program are amorphous silicon thin films, polycrystalline thin films, III-V PV devices made from elements in columns III and V of the periodic table, and new approaches for using crystalline silicon.

AMORPHOUS SILICON THIN FILMS

Amorphous silicon is a disordered material without the crystalline structure of the silicon used in the semiconductor industry. Figure 1 schematically shows the atoms in amorphous silicon material (1). However, amorphous silicon absorbs solar radiation much more efficiently than does crystalline silicon, with dramatic implications for the amount of material needed and the future cost of production of the fully developed technology. Approximately 200 times less silicon is required for amorphous silicon PV devices than is needed for crystalline silicon devices. Amorphous silicon conversion efficiencies are respectable--more than 12% total area efficiency for small laboratory devices. An important research issue for amorphous silicon has been a 10%-30% decline in the conversion efficiency of production devices when they are exposed to sunlight.

POLYCRYSTALLINE THIN FILMS

Polycrystalline thin films of copper indium diselenide (CuInSe_2 , abbreviated CIS) or cadmium telluride (CdTe) also absorb solar radiation much more efficiently than single-crystal silicon does. Again, small amounts (thin films) of material are needed so that future production costs for polycrystalline thin-film devices are expected to be lower than those for crystalline silicon PV devices. Like costs for amorphous silicon, costs for a fully developed polycrystalline thin-film technology are likely to be dominated by the costs of a sheet of glass onto which the polycrystalline thin films are deposited and, perhaps, a second sheet of glass to complete an environmentally-protected PV sandwich. The thin films are polycrystalline, again unlike single-crystal silicon, and both CIS and CdTe devices have achieved 12% total area efficiencies while showing promise of stabilities similar to those of conventional crystalline silicon technology. Figure 2 shows the arrangement of atoms in the chalcopyrite crystal structure of CIS material (2). Finally, researchers have explored techniques for making efficient thin-film devices from polycrystalline silicon; the films are actually quite thick since they are about 50 times thicker than those used in thin-film technologies. Figure 3 shows the nature of polycrystalline silicon material (3).

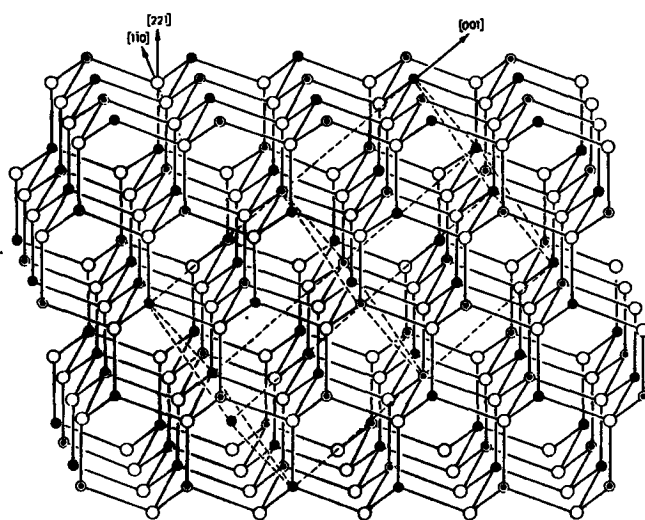


Figure 2. Chalcopyrite crystal lattice structure, (110) projection. Unit cell is indicated by dashed lines. ●, Cu; ○, In; ○, Se.

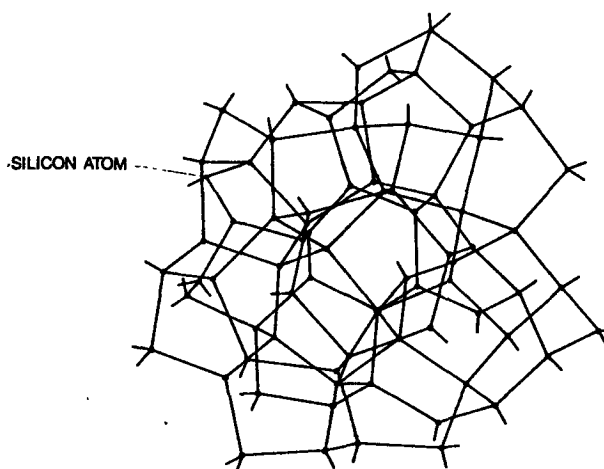


Figure 1. The lines connecting the dots (silicon atoms) represent the chemical bonds in amorphous silicon material

CRYSTALLINE TECHNOLOGIES

So-called III-V technologies are crystalline materials based on elements from columns III and V of the periodic table. Gallium arsenide (GaAs) is the most widely studied representative of these materials. III-V materials are highly efficient solar absorbers; thin films are sufficient for making PV devices. However, it is costly to make single-crystal thin-films using III-V materials, so III-V PV devices, which have had solar conversion efficiencies well above 30%, may be applied to solar concentrator technologies in which costly, small-area, high-efficiency devices can be tolerated. Indium phosphide (InP) is another III-V material for which high-efficiency devices have been made. InP may be important for PV applications in space because it is relatively resistant to damage from radiation. Figure 4 shows the orderly single-crystal arrangement of atoms in the zinc blende structure characteristic of III-V materials (4).

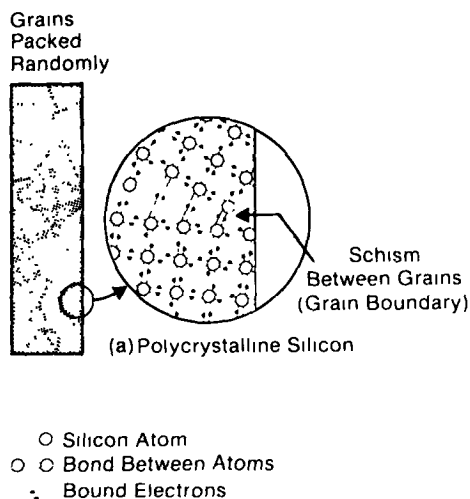


Figure 3. Polycrystalline silicon is made up of randomly packed grains, each of which is a single crystal of silicon.

PV DEVICES

Regardless of the technology or crystallinity of the materials, the heart of a PV device is a voltage arising between the junction of two or more layers having different electrical properties. For example, an n-type amorphous silicon layer in contact with an undoped intrinsic layer in contact with a p-type amorphous silicon layer results in a voltage within the layers that acts on electrons freed by the sunlight incident on the device. Electrical contacts over the entire back area of the device, and either narrow strip contacts or transparent electrical contacts over the front area, connect the PV device to loads or electric power conditioners. The junction in a CIS device comes from contact with another polycrystalline thin-film layer of CdS, whereas the junction in a GaAs device is often designed as that resulting from contact between n-type and p-type layers. A significant challenge in making PV devices is preparing these layers over large areas while maintaining homogeneity in the material properties of the layers. Figure 5 shows different junction possibilities for PV devices (3).

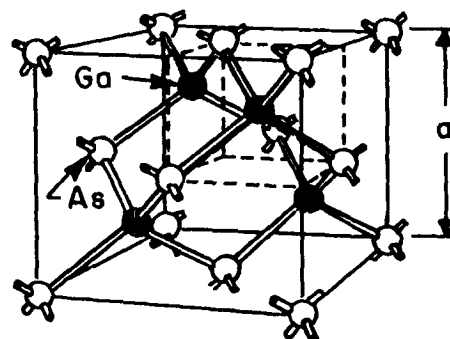


Figure 4. Zinc Blende (GaAs, GaP, InSb, etc.) Single crystal structure.

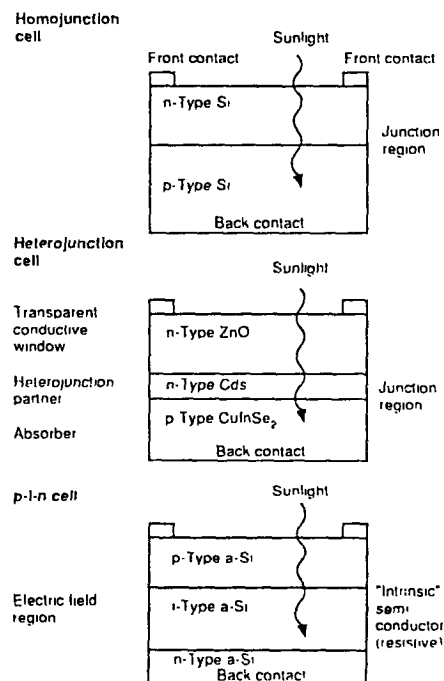


Figure 5. Different solar cell structures.

RESEARCH PROGRESS

Figure 6 shows the increase in conversion efficiency for different PV technologies over the past decade (6). It is possible that progress can continue for another decade at the same rate because the theoretical conversion efficiencies of PV devices are much higher than the efficiencies shown in Figure 6. Figure 7 shows the decrease in the cost of

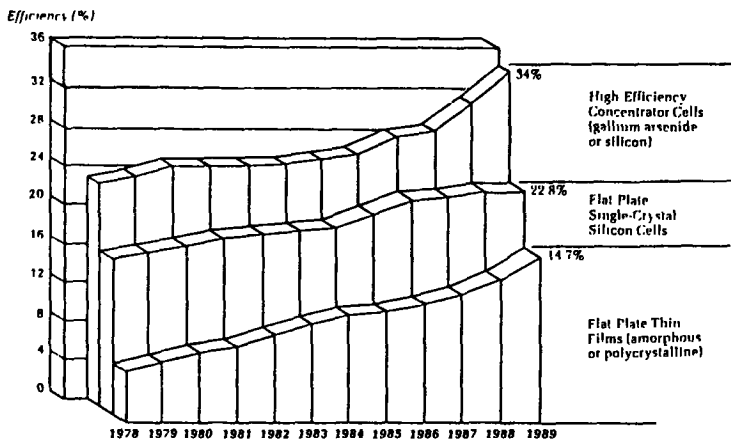


Figure 6. The efficiencies of laboratory cells increased markedly from 1978 to 1989.

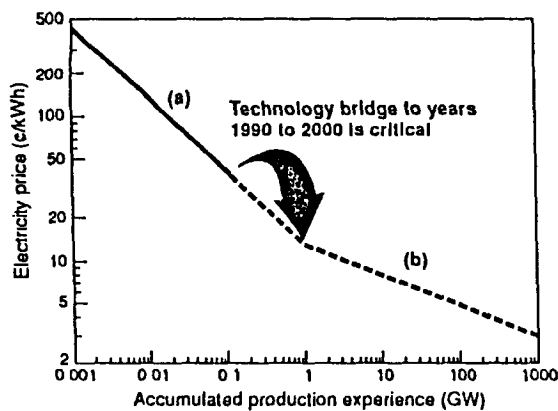


Figure 7. Dramatic cost reductions should continue through the end of the century as production increases. (a) price reduction of 68% achieved per tenfold increase in production experience; (b) price reduction of 40% anticipated per tenfold increase in production.

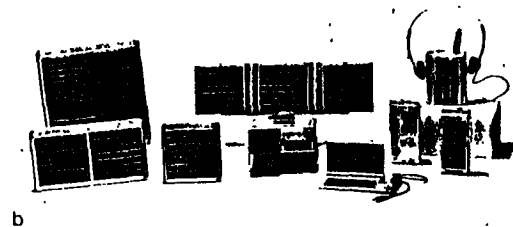
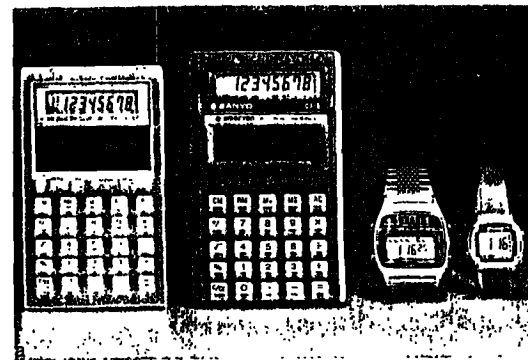


Figure 8. Example of consumer applications: (a) pocketable calculators and wrist watches, and (b) pocketable tape recorder, television, radio, and battery chargers. (Courtesy of Fuji Electric Co., Ltd.)

electricity produced by PV systems over the past decade and the expected future cost decreases that will occur as production levels increase (7). An early study suggested that these cost reductions were well within the potential of PV technologies, especially the thin-film technologies, because of their greatly reduced materials requirements (8). Efficiency increases and cost reductions, both past and future, provide the strong interest in PV by companies and countries around the world.

COMMERCIAL APPLICATIONS

Consumer products were a highly visible application for PV technologies during the 1980s. Solar-powered calculators, with annual sales of about 100 million calculators, are usually powered by amorphous silicon thin films (5). Solar-powered watches and clocks are among other consumer product applications (Figure 8) for amorphous



Figure 9. These outdoor lights are powered by photovoltaics.



Figure 10. PV-powered global positioning system at China lake.

silicon PV devices (9). Sailboat owners have bought PV power supplies for years, while car sunroofs, street address lighting, and outdoor lighting (Figure 9) are consumer products leading to new markets (3) in this area.

So-called stand-alone PV applications are those applications not connected to an electric utility. Military applications provide many good examples--Figure 10 shows a PV-powered global positioning system used by the Navy (10). The Navy performed a study in 1986 identifying more than 21,000 cost-effective PV applications (3). Military applications of PV for communications or navigation often incorporate diesel engine units for backup. Another stand-alone application--water pumping--is shown in Figure 11 (11). This stand-alone application of PV would not necessarily have diesel backup when there is water storage. Three additional noteworthy aspects of Figure 11 are: 1) the module is made from polycrystalline thin-film CdTe. 2) the manufacturer is British, and 3) the customer is international--Saudi Arabia, in this case. Telecommunications, village power for Third World villages, warning signals, remote monitoring, isolated lighting, cathodic power protection, and many other remote power requirements provide general categories for thousands of stand-alone applications of PV (12).

Grid-connected or utility applications are an important category in which the long-term impact of PV can have enormous importance for the United States and the world because of the size of the market. Utility systems (Figure 12) have been relatively small, with only a handful of systems built on the order of a megawatt (MW) or so in size (3). Instead, utilities have identified high-value energy markets yielding thousands of smaller systems installed within utilities to supply microwave repeaters, cathodic protection of pipelines, telmeters, lighting, remote switching, etc. (6). The Electric Power Research Institute estimates

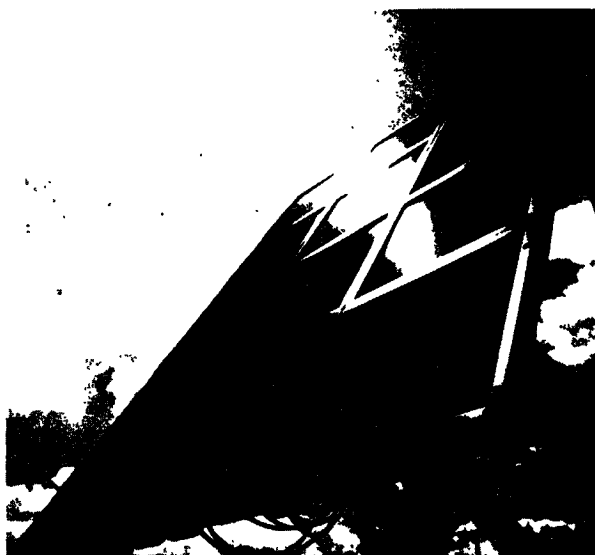


Figure 11. A 54 W thin-film CdTe array for water pumping deployed by BP Solar in Saudi Arabia.

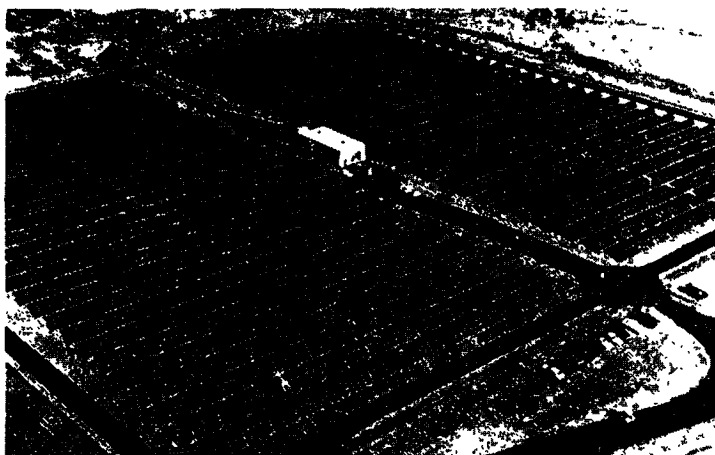


Figure 12. Near Sacramento, California, these arrays produce about a megawatt of power for the Sacramento Municipal Utility District.

that the potential utility-owned PV system market will be some 40,000 installations totalling over 11 MW by the year 1996 (13). Grid-connected houses (Figure 13), PV-powered pumps for swimming pools, and grid-connected commercial buildings are of interest for some utilities (14) because of land limitations or because of the demand-side management opportunities in these applications.

One of the oldest PV markets, although small, is for space system power supplies (Figure 14) because PV is very cost effective for satellite applications. A rapidly increasing market is the international market, because PV can provide village lighting, water pumping, and refrigeration for medical supplies more reliably and cheaper than small

diesel or gasoline generators. This international market is not just an equatorial market, but rather one where remoteness and need combine to make PV a cost-effective choice (Figure 15) (15). Finally, spin-off applications of PV R&D include thin-film transistors of amorphous silicon and optoelectronic devices using III-V materials.

International market results are shown in Figure 16, which shows worldwide PV shipments and country shares of this market activity (7). Note that a recent estimate for the 1991 world market sales is between 58 and 62 MW (16). This steady market growth of PV has attracted companies throughout the world. The largest of all future markets is expected to be the U.S. utility markets. Although market forecasts are highly uncertain, one prediction for the U.S. utility market alone is between 1 GW and 5 GW installed during the next decade, with almost 500 GW cumulative installed by the year 2030 (12, 17). This market size is big enough to interest most large companies, because it represents a \$1 trillion market over the 40-year period.

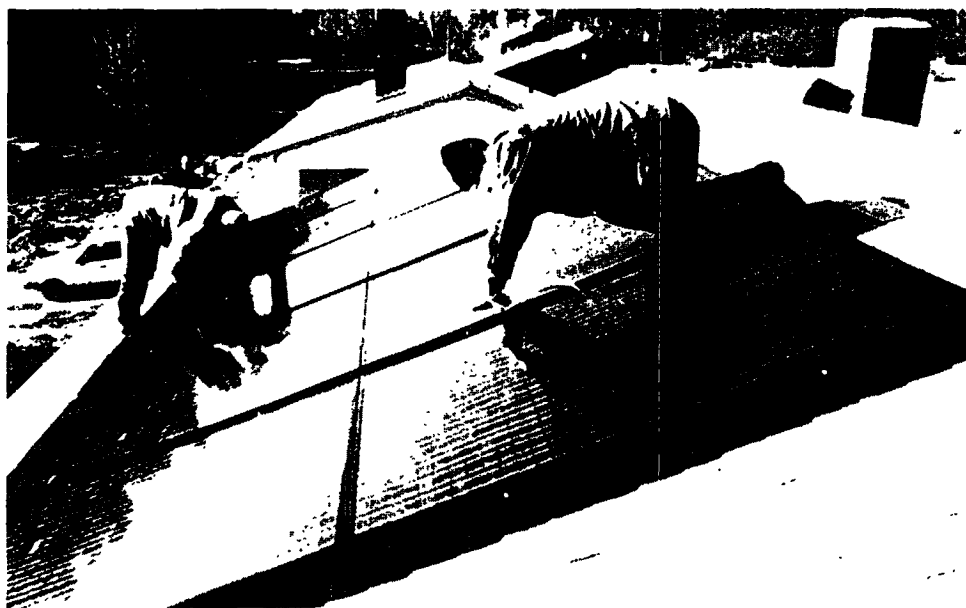


Figure 13. The Gardner study has earned a high degree of confidence in PV's system reliability and interaction with the distribution system.

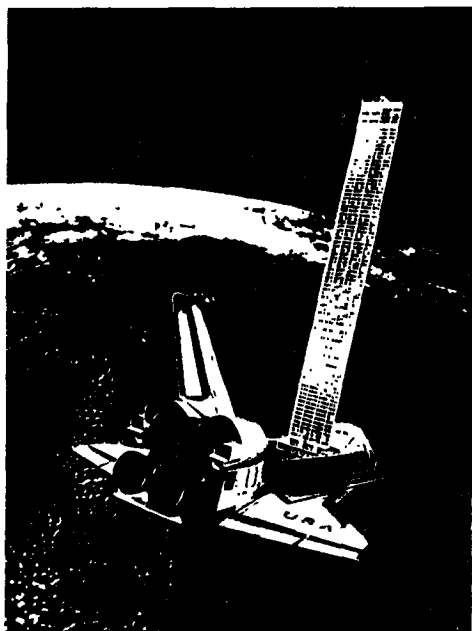


Figure 14. Discovery Shuttle with Lockheed solar panel.

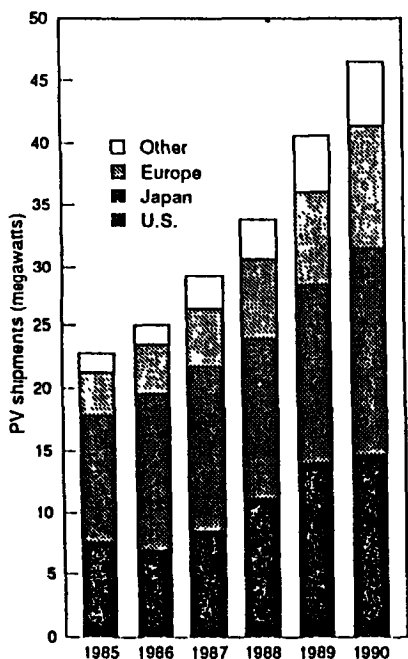


Figure 16. The U.S. share of the photovoltaics market has climbed to about 35%. (Source: PV News, February 1991)



Figure 15. A photovoltaic power system in a remote community of Canada's far north

TECHNOLOGY TRANSFER

The transfer of a technology developed with federal funds can take place in several ways. One example would be a U.S. industry licensing a technology developed by NREL. Another example could come from cooperative R&D projects involving NREL and industry researchers. As federal laboratories have tried to help U.S. industry in the international marketplace, seven technology transfer mechanisms have come into use. They are: 1) subcontracted R&D to industry using federal/NREL funds, 2) cooperative R&D agreements (CRADAs), 3) industry-sponsored R&D (what NREL calls Work for Others), 4) user facilities within NREL, 5) technology licenses, 6) research exchanges, and 7) information dissemination through research publications, workshops, and conferences. For over a decade, as mentioned earlier, NREL has worked closely with U.S. industry to develop PV technologies through R&D subcontracts. The most recent mechanism, CRADAs, arose from the National Competitiveness Technology Transfer Act of 1989 (18). A common CRADA might involve NREL scientists working with private industry scientists on an agreed-upon research project involving no exchange of funds. A signed agreement provides protection for intellectual property resulting from the research project for 5 years; i.e., the research information is protected from Freedom of Information Act inquiries. CRADAs are becoming today's currency for technology transfer in the national laboratories, consistent with the following definition for technology transfer: "Technology transfer is collaborative research and development between laboratory researchers and industry researchers for the purpose of aiding industry's commercialization of products and services." CRADAs can involve more than one private sector entity so that joint ventures

or consortia of national laboratories, PV manufacturers, electric utility suppliers, and electric utility end users are possible. Such vertically integrated joint ventures or consortia have the potential to be the government/private sector partnerships of the future.

As new photovoltaic technologies come of age and NREL researchers reach out to U.S. industry, NREL sees a period of even closer interaction with the U.S. private sector for the purpose of creating the nation's photovoltaic future.

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